Stiffness requirements for baseplates

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ABSTRACT: The CC-Method is widely used to design fastenings to concrete. Using the method, it is possible to calculate the resistance of single fasteners, as well as of groups of fastenings, under arbitrary loads. For groups of fastenings, the CC-Method assumes a rigid baseplate. International standards for fastenings require the baseplates to be “sufficiently stiff”, but do not give guidance on the design of the baseplate. The validity of an approach to insure sufficient baseplate stiffness by limiting bending stresses is investigated in this paper.

Keywords: baseplate, stiffness, finite-element simulation

1 INTRODUCTION

The Concrete Capacity Method for calculating the resistance of fastenings to concrete was developed at the University of Stuttgart (Fuchs/Eligehausen/Breen (1995)). The CC-Method can be used to design a large variety of fastenings to concrete including grouped fasteners connected to a common baseplate.

For grouped fastenings, the forces in the individual anchors must be calculated from the actions on the baseplate. The CC-Method assumes that this is done using the theory of elasticity (CEB (1997) or EOTA Annex C (1997)) (Figure 1). The following assumptions are made for a bending moment and/or normal force acting on the baseplate, which are similar to those for the design of reinforced concrete sections:

- the baseplate is stiff, strains are distributed linearly through the cross-section of the baseplate (corresponding to the “Bernoulli-Hypothesis” in reinforced concrete).
- the stiffness of the fasteners is equal to the steel stiffness, i.e. the slip of the fasteners is neglected.

The modulus of elasticity of the concrete depends on the concrete strength, however, it can be taken as E_c = 30,000 N/mm².

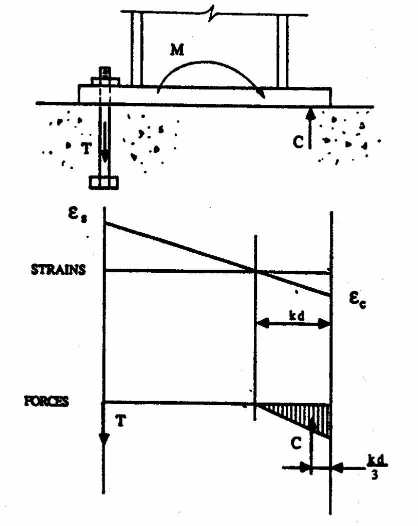

Figure 1: Stress and strain distribution assuming a stiff baseplate

Application of this approach is illustrated in Figure 2 for a box section welded to a baseplate. The required baseplate thickness is calculated by limiting the bending stresses in the baseplate. Therefore the bending stresses averaged over an area of 2*t+s

(Mallée & Burkhardt (1999)) at the edge of the box section (t = baseplate thickness and s = box section thickness) under the design actions, must be lower than the design steel yield strength. The baseplate thickness t must be increased until equation (1) is fulfilled:

$$\sigma_{sd} \le f_{yd} \qquad (1)$$

This criterion prevents yielding of the baseplate and thus large deflection will not occur.

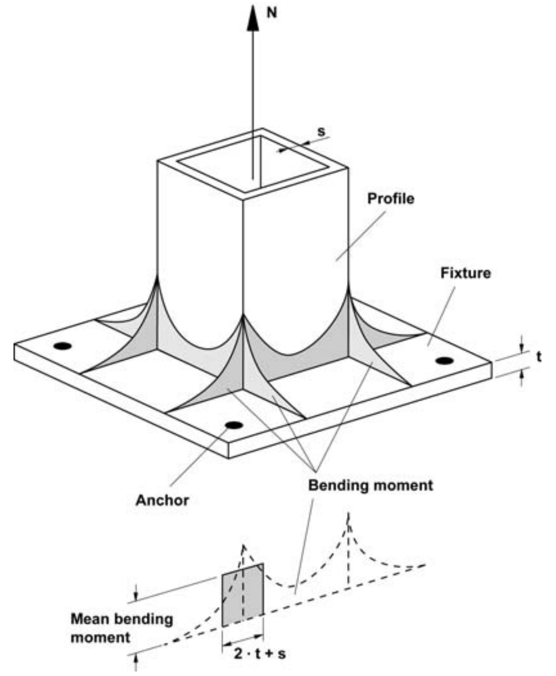

Figure 2: Calculation of the critical bending moment (Mallée & Burkhardt (1999))

2 LITERATURE REVIEW

Schneider (1999) performed finite-element (FE) studies on fastenings with four anchors and bending in one and two directions combined with an axial compression force. The distances between the anchors were very large relative to the fastener embedment depth. The position of the profile on the baseplate was varied (Figure 3).

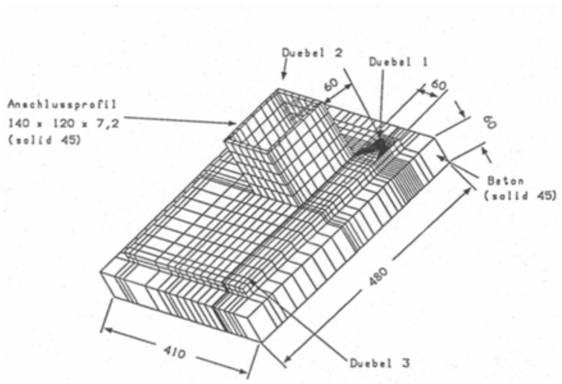

Figure 3: FE-Model with eccentrically mounted profile (Schneider (1999))

Mallée & Burkhardt (1999) performed tests on groups with four undercut anchors loaded by eccentric tension force. Additionally, numerical studies of this construction were carried out.

While Schneider (1999) determined that the tension stresses in the fasteners were often much larger than the values calculated with the CC-Method, the results of Mallée & Burkhardt (1999) agreed with the values obtained with the CC-Method.

In Table 1 the parameters of the numerical and experimental investigations are shown. The symbols in the column headers are illustrated in Figure 4.

Table 1: Summary of experimental and numerical tests and Results investigations by Schneider (1999) and Mallée & Burkhardt (1999)

		s_x	s_y	Prf. l_x	Prf. l_y	e_1	e_2	N [kN]	M_x [kNm]	M_y [kNm]	Anchor stiffness	h_{ef} [mm]	t_{fix}	Z_{FE}/Z_{CC}
Schneider (1999)	sym. loaded baseplate (1)	350	280	140	120	-	-	-	-	-	24	80	30	0,95
													25	1,00
													22	1,05
													20	1,08
													18	1,11
													16	1,14
	asym. loaded baseplate (2)					-	-						30	1,06
													25	1,14
													22	1,19
													20	1,22
													18	1,25
													16	1,28
	asym. loaded baseplate, ecc. profile (3)					70	45						30	1,37
													25	1,57
													22	1,72
													20	1,83
													18	1,95
													16	2,07
Mallée/Burkhardt (1999)	200/200, small profile, bending in one direction (1)	200	200	80	80	-	-	0,0	5,6	0,0	40	60	24	0,94
								5,0	5,0	0,0			24	0,95
								-6,1	6,1	0,0			26	0,91
	200/200, small profile, bending in two directions (2)							0,0	3,3	3,3			29	0,98
								3,1	3,1	3,1			28	0,99
								-3,5	3,5	3,5			31	0,95
	200/500, small profile, bending in one direction (3)	500		200	200			0,0	13,2	0,0			33	1,04
								10,6	10,6	0,0			33	0,99
								-16,1	16,1	0,0			38	1,07
	200/500, small profile, bending in two directions (4)							0,0	4,9	4,9			29	1,03
								4,4	4,4	4,4			29	1,04
								-5,3	5,3	5,3			31	1,01
	200/500, large profile, bending in one direction (5)			400	400			0,0	13,2	0,0			20	1,01
								10,6	10,6	0,0			20	0,99
								-16,1	16,1	0,0			20	1,03
	200/500, large profile, bending in two directions (6)							0,0	4,9	4,9			20	0,94
								4,4	4,4	4,4			20	0,95
								-5,3	5,3	5,3			20	0,94

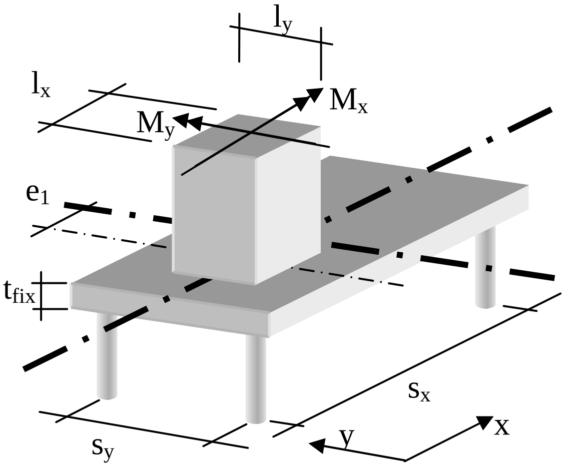

Figure 4: Illustration of the symbols used in Table 1

In Figures 5 and 6 the loads in the fasteners determined using the FE analysis are compared with the values according to the CC-Method (The different results might be explained by the different applied normal forces (compression and tension) and assumed anchor stiffness (comp. Table 1)).

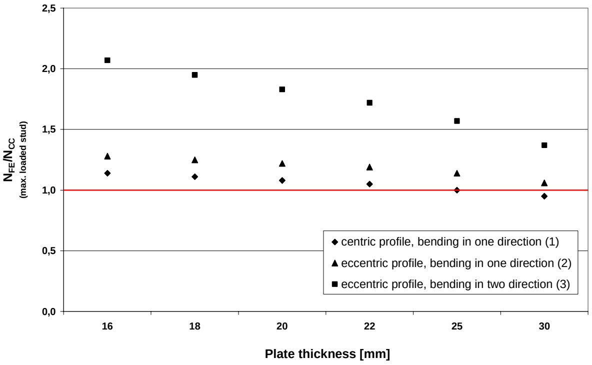

Figure 5: Results of the numerical investigations compared by Schneider (1999) to the CC-Method

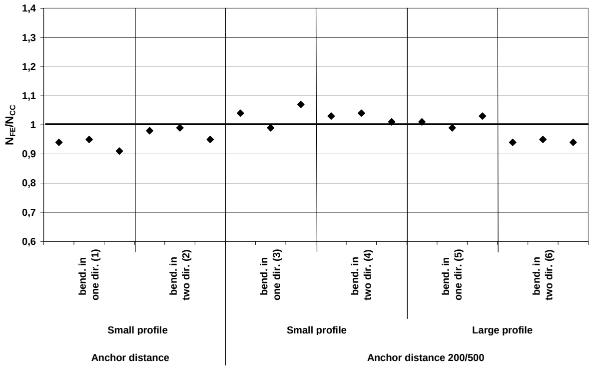

Figure 6: Results of the numerical investigations by Mallée & Burkhardt (1999) compared to the CC-Method

3 FINITE-ELEMENT CALCULATIONS

According to the results of Schneider (1999), the forces in the anchors can be much higher than calculated ones using elastic theory. Therefore it is likely that the strength of the fastening will be lower than calculated by the CC-Method. To determine the parameters that may have a significant influence on the fastener stresses, numerical calculations were performed using the fastenings already investigated by Schneider (1999). While the earlier authors modelled the baseplate only and assumed a certain stiffness of the anchor, in these investigations baseplate, anchors and concrete were modelled to study the influence of the baseplate thickness on the concrete cone failure load.

All of the baseplates were loaded by a combined bending moment and a compression force. Groups with 4 and 6 anchors with bending in one direction and with 4 anchors with bending in two directions were simulated. Additionally, the location of the attached profile on the baseplate was varied (Table 2).

Table 2: Parameters varied in the FE calculations

	No. studs	Dim. of plate [mm]		Project. end of plate [mm]	Bending		Eccentr. profile [mm]	
		X	Y		one axis	two axes	X	Y
1	4	330	400	25	X		-	-
2	4				X		-70	-
3	6	530	400		X		-	-
4	6				X		-100	-
5	4	330	400			X	-	-
6	4					X	-70	46,7

To investigate the influence of the baseplate thickness, three thicknesses for each of the constructions shown in Table 2 were used. The first thickness was determined from the design resistances of the fasteners. The second thickness was calculated using the ultimate loads of the fasteners. The third baseplate thickness was three times as thick as the first one, i.e. very stiff.

As fastening elements headed steel studs were used in the simulations.

4 THE FINITE-ELEMENT PROGRAM

The program MASA, developed by Ožbolt, is intended for nonlinear three-dimensional (3D) smeared fracture finite element analysis of structures made of quasi-brittle materials. Although different kind of materials can be employed, the program is mainly intended to be used for the nonlinear analysis of concrete and reinforced concrete (RC) structures in the framework of the local or nonlocal continuum theory, i.e. damage and fracture phenomena are treated in a smeared way (smeared crack approach).

The employed material model (constitutive law) is based on the general microplane model for concrete. The reinforcement is modeled by an uniaxial elasto-plastic stress-strain relationship with or without strain hardening.

In the numerical analysis of materials which exhibit fracture and damage phenomena, such as concrete, one has to use a so-called localization limiter to prevent localization of damage into a zero volume and to make the analysis independent of the size and allayment of the finite elements. In the program MASA two approaches can be used. The first is the relatively simple crack band approach and the second one is more general nonlocal approach of integral type. In this analysis, the first approach was employed.

In MASA, a structure can be discretized by four or eight node solid finite elements. Modelling of reinforcement bars can be performed with two-node truss elements or alternatively by beam elements. Three solution strategies are available to perform the nonlinear iterations: Constant Stiffness Method (CSM), Tangent Stiffness Method (TSM) or Secant Stiffness Method (SSM). An explicit formulation of the stiffness matrix is used and thus loads or displacements are applied incrementally.

In the present study the Secant Stiffness Method was used and the load was applied by using displacement increments. The finite element mesh generation was performed with the software FEMAP®, which is also used for pre- and post-processing of data for MASA. The concrete was unreinforced and only three-dimensional elements (four nodes) were used for steel and concrete (Figure 7).

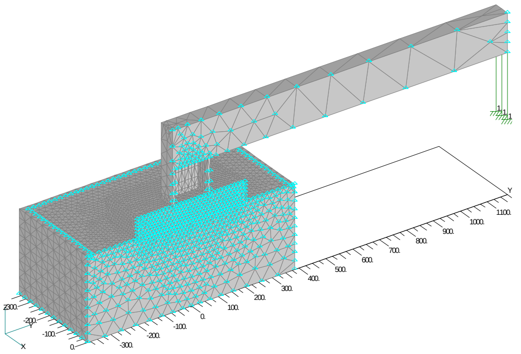

Figure 7: Finite-element model of a baseplate with four headed studs attached to a concrete block (half model, one central axis)

5 RESULTS

In Table 3 the results of the numerical studies are shown. The number in the first column coincides with the numbering in Table 2.

Table 3: Results of the simulations and the corresponding values of the CC-Method

Baseplates								Max. loaded stud	
No.	Plate thickness			CC-Method		FE-calc.		Ultimate load N_{Rm}	
	CC-Method		FE-calc.	Ultimate load F_{Rm}	Inner lever arm	Ultimate load F_{Rm}	Inner lever arm	CC-Method	FE-calc.
	using N_{Rd}	using N_{Rm}							
	[mm]	[mm]	[mm]	[kN]	[mm]	[kN]	[mm]	[kN]	[kN]
1	22,2	34	20	48,2	346	46,28	308	70,1	77,5
			34			49,49	323		78,3
			70			57,62	356		79,9
2	29,3	43	26			34,26	239		79,5
			43			41,32	277		79,9
			85			56,34	353		78,8
3	30,2	46	28	80,9	401	78,6	251		82,4
			46			71,94	316		73,7
			90			92,46	384		79,1
4	42	67	40			41,77	288		79,8
			67			55,86	342		81
			130			87,91	394		79,4
5	22,9	34	20	35,8	334	34,27	261		82,1
			34			34,92	316		76,3
			70			42,44	351		78,2
6	28,5	43	26			20,1	243		80,2
			43			23,63	282		76,4
			85			38,23	354		80

In all calculations failure was caused by concrete cone breakout of the tensioned studs. The ultimate tension load in the studs was constant but slightly higher (about 10%) than the values according to the CC-Method (Figure 8).

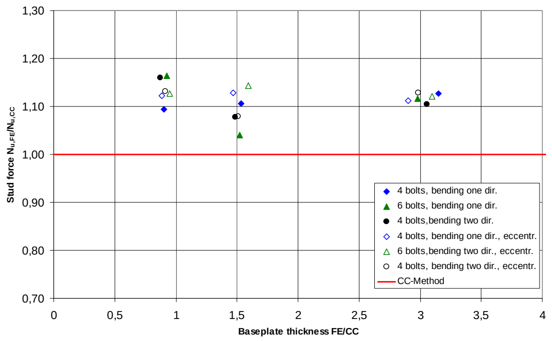

Figure 8: Ultimate loads in the tensioned studs, comparison between FE results and the CC-Method (Baseplate thickness relative to the value required by the CC-Method)

A group with 4 anchors and a centrically welded profile reached the ultimate load, which is calculated with the CC-Method, in all three cases of plate thicknesses. The other two stud/force arrangements (Table 2, No. 3 and 5) with centrically attached columns also reached the ultimate load predicted with the elastic theory (Figure 9).

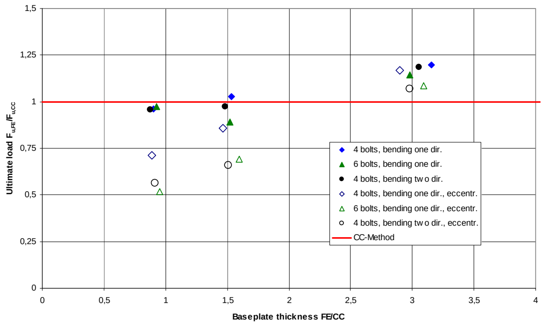

Figure 9: Ultimate load (FE calculation) of the construction compared to the value of the CC-Method taking into account the design resistance of the fasteners

If the profile was located near the tensioned studs, the ultimate load of the construction in the simulation was lower than the value calculated with the CC-Method.

By using the required plate thickness, which was determined from the design values for the resistances of the studs, the ultimate load of the construction was 30% lower than the value according to the CC-Method (4 studs, bending in one direction). For groups with 6 headed studs and bending in one direction or with 4 headed studs and bending in two directions, the maximum load on the construction was about 46% lower than the values calculated with the CC-Method (Table 3).

The reduction of the ultimate load mainly results from a shorter internal lever arm of the static forces between the baseplate and the concrete (Figure 10). Due to a shorter lever arm, the forces in the fastenings are higher than calculated by the CC-Method at the same load level.

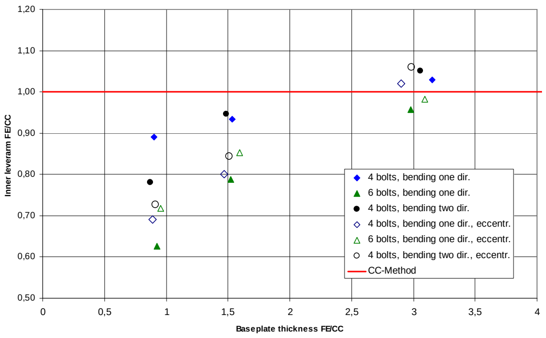

Figure 10: Reduction of the lever arm of the internal forces, comparison between FE calculation and the CC-Method

The cause for this shorter inner lever arm is the compression force between the baseplate and the concrete. Thin baseplates (thickness calculated according to the CC-Method) have larger elastic deflection. At loads above the design value determined with the CC-Method, some parts of the plate will begin to yield. This results in a compression force under the plate, which moves towards the welded profile as plate thickness decreases (Figure 11).

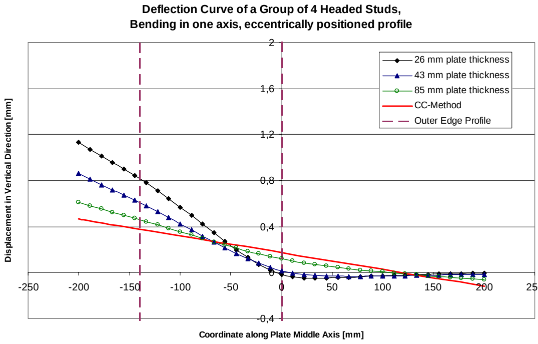

Figure 11: Bending of the baseplate (No. 2 in Table 2) at the ultimate load for different thicknesses

If the attached profile edge is far away from the compressed baseplate edge, the compression force decreases the internal lever arm and therefore the ultimate load of the construction is greatly reduced.

As shown in Figure 12, however, even if the plate thickness is calculated using the ultimate resistance of the fasteners, the ultimate load of the construction may be still less than the value according to the CC-Method. Since no yielding in the plate can occur (see (1)) for this greater plate thickness, another explanation for the reduction at the ultimate load must exist.

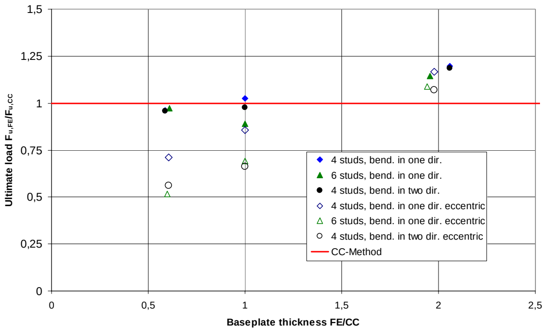

Figure 12: Ultimate load of the construction compared to the values of the CC-Method taking into account the ultimate resistance of the fasteners

The stiffness of the fasteners has a strong influence on the internal lever arm even during elastic bending of the baseplate. In this study very stiff headed studs were used (N_u=70kN, s_u=0,41mm => k_S=70/0,41=170 kN/mm).

In comparison to this, Schneider (1999) with 24 kN/mm and Mallée & Burkhardt (1999) with 40 kN/mm used significantly less stiff fasteners. Nevertheless, a stiffness of 170 kN/mm for headed studs is a practicable value.

If the stiffness of the fastener is high, the elastic deflection of the baseplate has an influence on the location of the resulting compression force between the baseplate and the concrete. If the plate cannot lift up from the concrete surface, the compression force under the plate moves towards the attached profile. This explains the behavior observed in Figure 12.

The positive effect of less stiff fasteners is illustrated in Figure 13. The results of numerical simulations (Figure 14) confirm this assumption:

With an eccentric profile the distance to the tensioned fasteners is decreased such that the baseplate can not bend that much like with a centric profile. This results in less up-lift of the plate which can only be leveled out by more flexible fasteners. Then the resultant compression force stays under the baseplate at the edge of it and the inner lever arm is as large as assumed by the CC-Method.

In Table 4 the results of both simulations (stiff and flexible studs) are listed.

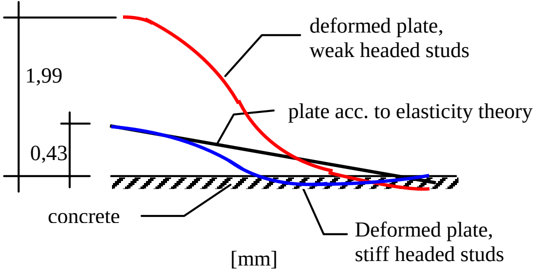

Figure 13: Theoretical behavior of the baseplate using flexible fasteners

Stud stiff-ness	Ultimate load		Innerer lever arm		max. loaded stud			
					Ultimate load		Displacement	
	CC [kN]	FE [kN]	CC [mm]	FE [mm]	CC [kN]	FE [kN]	CC [mm]	FE [mm]
stiff	48,1	41,3	346	277	70,1	79,9	-	0,43
weak	48,1	55,1	346	349	70,1	78,8	-	1,99

Table 4: Results of simulations with flexible and stiff fasteners, comparison with the CC-Method

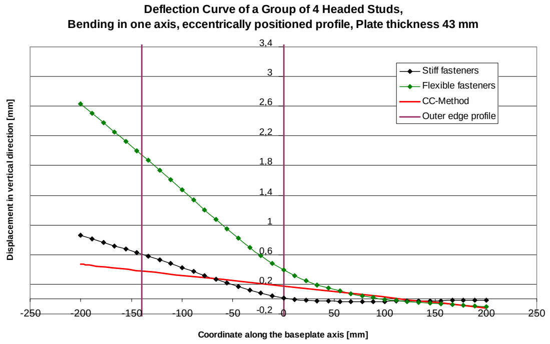

Figure 14: Deflection of the baseplate with different stiffness of fasteners

The numerical simulations showed an influence of the following parameters on the ultimate load of a construction with grouped fasteners:

- thickness of the baseplate
- stiffness of the fasteners
- size of the baseplate
- size of the welded profile
- position of the profile
- number of fasteners
- load combination

Since the parameters are interdependent, further research has to be done to describe the problem quantitatively and qualitatively.

6 SUMMARY

The design of baseplates according to elastic theory, which is assumed by the CC-Method, leads in most applications to satisfactory results. In some cases, however, constructions designed with the required baseplate thickness according to the CC-Method do not reach the predicted ultimate load.

Two main influencing factors which lowered the ultimate load of the constructions in the simulations were determined: baseplate thickness and fastener stiffness. For very stiff fasteners, a large distance between the profile and the compressed baseplate edge led to higher stresses on the studs and less ultimate load of the construction.

Further research is necessary to determine the importance of the numerous influencing parameters. This work will be conducted as part of an ongoing research project. The aim is to develop design rules to ensure that the CC-Method yields safe designs for all baseplate constructions.

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